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Astrobiology in the Environments of Main-Sequence Stars: Effects of Photospheric Radiation

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Abstract. We explore if carbon-based macromolecules (such as DNA) in the environments of stars other than the Sun are able to survive the effects of photospheric stellar radiation, such as UV-C. Therefore, we focus on main-sequence stars of spectral types F, G, K, and M. Emphasis is placed on investigating the radiative environment in the stellar habitable zones. Stellar habitable zones are relevant to astrobiology because they constitute circumstellar regions in which a planet of suitable size can maintain surface temperatures for water to exist in fluid form, thus increasing the likelihood of Earth-type life.

1. Theoretical approach

The centerpiece of all life on Earth is carbon-based biochemistry. It has repeatedly been surmised that biochemistry based on carbon may also play a pivotal role in extraterrestrial life forms, if existent (e.g., Bennett & Shostak 2007). This is due to the pronounced advantages of carbon, especially compared to its closest competitor (i.e., silicon), which include: its relatively high abundance, its bonding properties, and its ability to form very large molecules as it can combine with hydrogen and other molecules as, e.g., nitrogen and oxygen in a very large number of ways (Goldsmith & Owen 2002).

In the following, we explore the relative damage to carbon-based macromolecules in the environments of stars other than the Sun using DNA as a proxy. We focus on the effects of photospheric radiation from main-sequence stars, encompassing the range between F0 and M0. Our models consist of the following components:

1. The radiative effects on DNA are considered by applying a DNA action spectrum (Horneck 1995). It shows that the damage is strongly wavelength-dependent, increasing by more than seven orders of magnitude between 400 and 200 nm. The different regimes are commonly referred to as UV-A, UV-B, and UV-C.

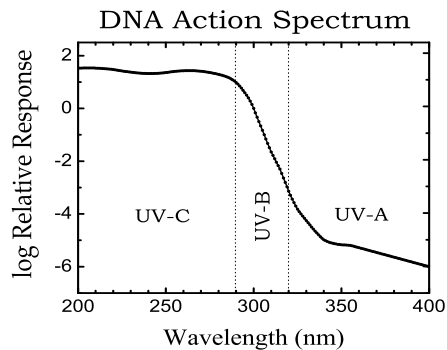


Figure 1. DNA action spectrum following Horneck (1995).

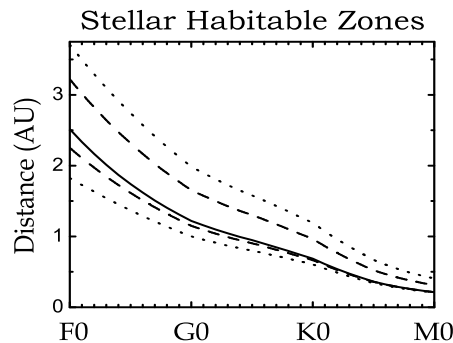


Figure 2. Stellar habitable zones for main-sequence stars of different spectral types. The dashed lines indicate the conservative HZ, whereas the dotted lines indicate the generalized HZ. The solid line denotes the Earth-equivalent position.

2. The planets are assumed to be located in the stellar habitable zone (HZ). Following the concepts by Kasting et al. (1993) and Underwood et al. (2003), we distinguish between the conservative and generalized HZ (see Fig. 2). The inner and outer edge of the conservative HZ are given by the onset of water loss and CO_2 condensation, respectively, whereas the inner and outer edge of the generalized HZ are given by the runaway greenhouse effect and the breakdown of greenhouse heating, respectively, needed to permit the existence of fluid water on the planetary surface.
3. Stellar photospheric radiation is represented by using realistic spectra, which take into account millions or hundred of millions of lines for atoms and molecules (Castelli & Kurucz 2004, and related publications). Clearly, significant differences emerge between the different spectral types, both concerning the total amount of radiation and their spectral distribution.

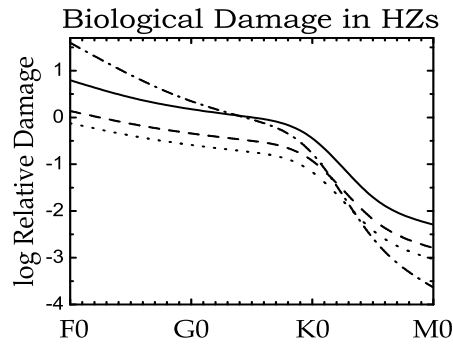


Figure 3. Biological damage to DNA for a planet at an Earth-equivalent position without an atmosphere (solid line), an atmosphere akin to Earth 3.5 Gyr ago (dashed line) and an atmosphere akin to Earth today (dotted line). The dash-dotted line refers to a planet without an atmosphere at 1 AU.

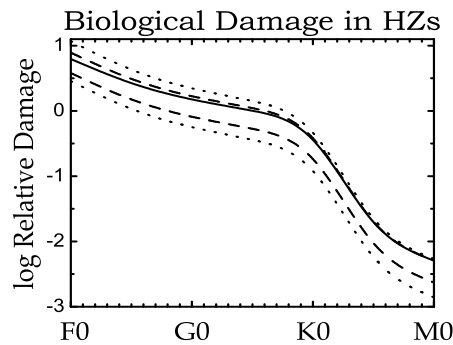


Figure 4. Biological damage to DNA for a planet (no atmosphere) at an Earth-equivalent position (solid line), at the limits of the conservative HZ (dashed lines) and at the limits of the generalized HZ (dotted lines).

4. We also consider the effects of attenuation by a planetary atmosphere. The following cases are considered: Earth as today, Earth 3.5 Gyr ago, and no atmosphere at all (Cockell 2002). For general discussions see, e.g., Guinan & Ribas (2002) and Guinan et al. (2003).

Our results are presented in Figs. 3 and 4. They show the relative damage to DNA due to photospheric radiation from stars between spectral type F0 and M0. The results are normalized to today's Earth, placed at 1 AU from a star of spectral-type G2V. We also considered planets at the inner and outer edge of either the conservative or generalized HZ as well as planets of different atmospheric attenuation.

2. Conclusions

Based on our studies we arrive at the following conclusions:

1. All main-sequence stars of spectral type F to M have the potential of damaging DNA due to UV radiation. The amount of damage strongly depends on the stellar spectral type, the type of the planetary atmosphere and the position of the planet in the habitable zone (HZ). Our results constitute a quantitative update and improvement of previous work by Cockell (1999).
2. The damage to DNA for a planet in the HZ around an F-star (Earth-equivalent distance) due to photospheric radiation is significantly higher (factor 5) compared to planet Earth around the Sun, which in turn is significantly higher than for an Earth-equivalent planet around an M-star (factor 180). Small modifications of this picture occur for different planetary positions inside their respective HZs.
3. Regarding the cases studied, we found that the damage is most severe in the case of no atmosphere at all, somewhat less severe for an atmosphere corresponding to Earth 3.5 Gyr ago, and least severe for an atmosphere like Earth today.

Our results are of general interest for the future search for planets in stellar HZs, the chief goal of future NASA search missions (e.g., Turnbull & Tarter 2003). Our results also reinforce the notion that habitability may at least in principle be possible around M-type stars, as previously discussed by Tarter et al. (2007). Note, however, that a more detailed analysis also requires the consideration of chromospheric UV radiation, especially stellar flares (e.g., Robinson et al. 2005).

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